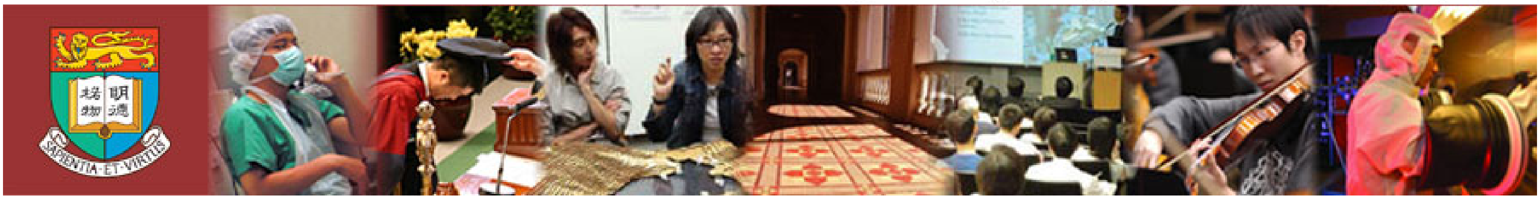

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Construction of System Restoration Strategy with PMU Measurements

Yunhe Hou, *Member, IEEE*, Shanshan Liu, *Member, IEEE*, and Zhijun Qin

***Abstract*—Power system restoration is well-recognized as one of the major technologies to improve system reliability. A high efficient restoration strategy is established and implemented with accurate information acquisition. Phasor measurement unit (PMU) provides a state-of-the-art information monitoring technology. In this paper, with PMU measurements, several algorithms are proposed to ensure complete observability of systems under regular operating conditions and during system restoration process. Case studies on IEEE 14, 30, 57, 118 and 300 – bus systems validate efficiency of the proposed algorithms.**

***Keywors*—System restoration, phasor measurement unit, binary optimization, observability**

I. Introduction

Following a partial or complete outage, sophisticated restoration strategies can minimize the disruption of energy services and promise a reliable, resilient and responsive electric supply. As the essential infrastructure, the high requirement of reliable electricity supply powerful reminder of the critical necessary for genetic decision support system of power system restoration[1].

High efficient restoration strategies design and implementation are all based on available information. During system restoration, to maintain the safety of a power system, almost all of constraints, such as steady-state constraints, dynamic constraints, even the electromagnetic constraints, should be involved. At different stages, information requirements are diverse. For instance, at the beginning stage of system restoration, restoration planers have to assess the system status before establish a restoration strategy; while, for the safety of implementation of each restoration action, violations should be detected. Furthermore, the system conditions during restoration are significantly different from the regular operating conditions[2]. Special considerations associated with different information requirements are needed. As a result, the monitoring system with high precision and communication speed is widely recognized as a critical component to implement power system restoration.

Phasor measurement unit (PMU), as the state-of-the-art information monitoring infrastructure, has the ability to measure the state of a power system accurately and frequently[3, 4]. Furthermore, with global positioning system (GPS) technology, PMUs synchronize several readings taken at distant points. Based on this technology, PMUs provide the truly synchronized voltages and currents measurements at diverse locations. It is believed that the data from PMUs would be much more accurate than the traditional data acquisition techniques. Today, hundreds of PMUs are in place in the U.S. and more are planned. PMUs provide a novel information acquisition method during system restoration.

Applications of PMUs in power systems have been widely carried out. Currently, the major research areas cover the real time system status monitoring, state estimation, voltage stability assessment, transient stability assessment, and small signal stability assessment. Another important application lies in optimal placement of PMUs to ensure the complete observability of the system[5]. However, few research works focus on utilization of PMU measurements during system restoration process at present. Currently, restoration planning is established based on the assumption that all of required information is available.

The purpose of this paper is to study the methodology of construction of system restoration strategy based on PMUs measurements. A novel algorithm is proposed to ensure the observability of each step during system restoration.

II. Development Of PMU

The objective of PMU is to implement the concept so called *Synchronized Phasor*, i.e., the phasor measurements that occur at the same time at different locations. In power systems, enormous sensors have been installed. These sensors monitor information at different location with considerable high accurate. However, common time is not available until the invention of PMU. As a result, information at different locations cannot be synchronized by traditional sensors. It significantly challenges the power system operation, which should be balanced instantaneously.

PMU is developed with time-stamped measurements. This concept has been defined by IEEE standard C38.118[6]. Two important definitions are shown as follows:

- Phasor: A complex equivalent of a simple cosine wave quantity such that the complex modulus is the cosine wave amplitude and the complex angle (in polar form) is the cosine wave phase angle.
- Synchronized phasor: A phasor calculated from data samples using a standard time signal as the reference for the measurement. Synchronized phasors from remote sites have a defined common phase relationship.

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According to the definition of IEEE C38.118, currently, both magnitudes and phase angles of the sine waves of voltages and currents are measured at the locations where PMUs are installed. To implement Synchronized phasor, PMUs synchronize from the common time source of a global positioning system (GPS) radio clock. The GPS receivers make possible the synchronization of several readings taken at distant points. Based on this technology, PMUs provide the truly synchronized voltages and currents measurements at diverse locations in a power grid to system operators. Benefit from the accurately time-stamped measurements, it is possible to compare two quantities at remote locations in real time. System status can be assessed by this accurate comparison as well. The basic diagram is illustrated in Fig.1.

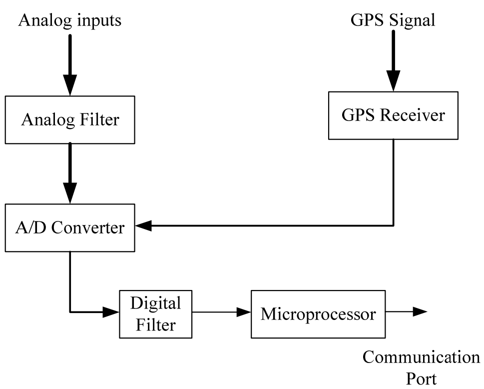

Fig. 1. The basic block diagram of PMU

Since the early 1990s, research projects on PMUs' applications have been widely carried out. These projects are collaborated with American Electric Power, Bonneville Power Authority (BPA), New York Power Authority, Southern California Edison (SCE), and Western Area Power Administration (WAPA). The applications of PMUs in the Western part of the United States have been started from 2002. California Independent System Operator (CAISO) has combined the PMUs with a real-time dynamic monitoring system (RTDMS), a workstation for offline analysis has been established. Meanwhile, many companies, such as BPA, Pacific Gas & Electric Co. (PG &E), SCE, and WAPA have carried out widely research on PMUs development. The deployment of real-time PMU data analysis, voltage, and dynamic stability assessment and data visualization applications were enhanced. A direct benefit is SCE's Power Systems Outlook software, which has been used for post-disturbance analysis and is currently demonstrating its real-time capabilities in the grid control center. Currently, the following companies are involved: California ISO , BPA , SCE , PG &E, BC Hydro & Power Authority; Alberta Electric System Operator; Arizona Public Service Company (APS), Sempra Utilities, ES BI Alberta, Los Angeles Department of Water and Power (LAD WP), PacifiCorp., Salt River Project (SRP), and WAPA [4].

Befits of PMUs for blackout prevention were shown on AEP system. AEP installed PMU before the 2003 blackout. The PMU captured the data during blackout and were used for the event analysis. As a result of the blackout of August 2003, the Eastern Interconnection Phasor Project (EIPP) has been established. Organized by EIPP, several PMU systems, i.e., AEP, Ameren, Entergy, NYPA, have sent data to Tennessee Valley Authority's (TVA) central PDC and then rebroadcasted back to the utility PDCs. Until now, many companies have been involved in EIPP, they are Ameren, AEP , American Transmission Company, ConEdison, Entergy, Exelon (ComEd/PECO), First Energy, Hydro One, Manitoba Hydro, Midwest ISO, NY ISO /NYPA , PPL, Southern Company, and TVA. Until the end of 2008, over 200 PMUs are in service across the North America, and approximately 20 systems are being installed and implemented for various applications.

III. Current Standards of PMU

To integrate measurement systems into power system environments, standards are critical. With this standard, the data output formats are specified to ensure the measurement produce comparable results. The synchrophasor standard will help ensure maximum benefits from the phasor measurements and allow interchange of data between a wide variety of systems for users of both real-time and off-line phasor measurements.

The need for PMUs' standard as well as the standard for synchrophasors has been recognized by IEEE since 15 years ago. The first standard, i.e., IEEE Std 1344-1995 standard for synchrophasors, was completed in 1995, and reaffirmed in 2001. The latest standard, IEEE Std C37.118-2005 was completed in 2005. The IEEE Std C37.118-2005 replaced the previous IEEE Std 1344-1995. The standard is not yet comprehensive - it does not attempt to address all factors of PMUs. Some important issues to be addressed, including definition of a synchronized phasor, definition of time synchronization, application of timetags, method to verify measurement compliance with the standard, and message formats for communication with a phasor measurement unit (PMU).

Although, the utilizations of PMUs are not limited by this standard, the primary purpose of this standard is to ensure PMUs' interoperability under steady-state conditions, i.e., during observation, signals of frequency, magnitude, and phase angle are constant. The reason is that in this standard, the timetag is defined as the time of the theoretical phasor represented by the estimated phasor, and then, a time near the center of estimation window will be selected normally. Therefore, the straightforward application of PMUs is to provide measurements of voltages and currents under steady-state conditions.

However, many recent researches show that the PMUs may be good for making measurements under various transient conditions. Actually, during a change in magnitude, phase angle, or frequency, two PMUs with different algorithms and/or different analog circuitries can be expected to yield different results for the same phasor measurement in a transient state. A potential method may be yielded based on the benchmark test.

To use PMUs, other standards may be needed with PMUs' interfacing:

- OPC-DA / OPC-HAD - A Microsoft Windows based interface protocol that is currently being generalized to use XML and run on non-Windows computers
- IEC 61850 - A standard for electrical substation automation
- BPA PDCStream - A variant of IEEE 1344 used by the Bonneville Power Administration (BPA) PDCs and user interface software

IV. Observability of Power Systems with PMU

The problem of PMU placement in power systems to ensure the observability is well recognized [5, 7-10] . In this research, PMU is assumed with capacity to measure voltage phasor at the bus where PMU installed and current phasors along the branches which are connected to the bus. Based on this understanding, the optimal PMU placement problem is modeled as a search problem to minimize the numbers of PMUs to cover all of buses in the network with depth of one. An illustrative example is shown in Fig.2. For instance, if two PMUs are installed at bus 1 and 3 respectively, complete observability can be obtained. However, if two PMUs are installed bus 4 and 5 respectively, bus 2 cannot be observed.

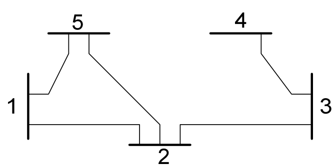

Fig.2. An illustrative example

In some research works, the optimal PMU placement problem is solved by some heuristic algorithms, such as tree search algorithm, genetic algorithm, simulated annealing algorithm, and immunity genetic algorithm [5, 8]. As high efficient heuristic algorithms, nonlinear constrains as well as realistic models of PMU are easy to be integrated. However, convergence property cannot be ensured theoretically at present. Another realistic consideration is the numbers of PMU channels, i.e., one PMU installed at a bus can only monitor limited phasors of current and voltage.

An algorithm is established to optimal placement of PMU to ensure complete observability of system will limited information channels of each PMU. For a system with N buses, mathematically, the algorithm is formulated as follows:

Algorithm 1:

$$\min \quad \mathbf{f}^T\mathbf{X} \tag{1}$$

$$\text{s.t.} \quad \mathbf{CX} > 0 \tag{2}$$

where $\mathbf{C}$ is the connection matrix of the power grid, i.e.,

$$\mathbf{C} = \left[c_{ij}\right] = \begin{cases} 1 & i = j \text{ or } i \text{ and } j \text{ are connected directly} \\ 0 & i \text{ and } j \text{ are not connected directly} \end{cases} \tag{3}$$

$\mathbf{X}$ is the binary decision vector of size N, ith element is 1 if a PMU is installed at the bus i and 0 if no PMU is installed at that bus; $\mathbf{f}$ is defined as if $\mathbf{Y} = 1 \cdot \mathbf{C}$ if $Y_i \geq M$, $f_i = \inf$, elase $f_i = 1$, where M is the limit of channels of a PMU.

Use the network illustrated in Fig.2 as an example. The connection matrix is

$$\mathbf{C} = \begin{bmatrix} 1 & 1 & 0 & 0 & 1 \\ 1 & 1 & 1 & 0 & 1 \\ 0 & 1 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 & 0 \\ 1 & 1 & 0 & 0 & 1 \end{bmatrix}$$

For ith column, the jth element identify whether bus j is connected with bus i ($c_{ij} = 1$) or not ($c_{ij} = 0$) by a branch. If two columns, say pth and qth, are added, all of no-zero elements identify that all of the buses connected with bus p and q directly. For example, summation of the second and third columns is $(1,2,2,1,1)^T$ means all of the buses are connected with either bus 2 or bus 3. As a result, if two PMUs are installed at bus 2 and bus 3 respectively, the complete observability can be obtained. The optimal placement of PMU is modeled as to find minimal numbers of columns of connection matrix with no-zero elements in summarizing vector. Furthermore, to consider the limit of PMU channels, the numbers of branches connected with a bus where the PMU installed should be limited. In other words, in connection matrix $\mathbf{C}$, the number of non-zero elements of the vector, which describes the candidate bus for PMU installed, should less than the number PMU channels. In the model described by (1) and (2), this constraint is modeled as a penalty function in objective function.

As a binary linear optimization problem, numerous high efficient algorithms have been developed and can be employed to solve the proposed model with limited computing time. Use IEEE 14-bus system as an example, as illustrated in Fig.3.

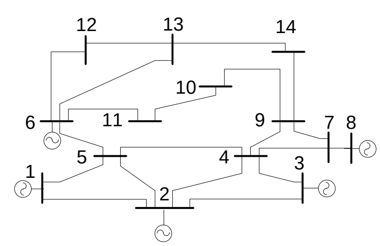

Fig. 3. Topology of IEEE 14-bus system

If the limit of channels of PMU is not considered, one of the optimal placements of PMU is on bus: 2, 6, 7 and 9. With different numbers of channels of each PMU, the optimal placements of PMUs are listed in Table I.

Table I: Optimal Placements of PMU In IEEE 14-Bus System

Numbers of Channels	Buses Installed PMUs
6	2,6,7,9
5	1,3,7,10,13
4	1,3,8,10,12,14

It should be noted that one channel is used to measure the phasor of the bus's voltage. As a result, the numbers of channels is M means the branches from the bus is less than M.

The optimal placements of IEEE 30-bus and 57-bus system is also listed in Table II

Table II: Optimal Placements Of PMU in IEEE 30-Bus And 57-Bus Systems

Numbers of Channels	Buses Installed PMUs	
	IEEE 30-Bus	IEEE 57-Bus
8	1, 7, 9, 10, 12, 18, 24, 25, 27, 28	1, 4, 6, 13, 20, 22, 25, 27, 29, 32, 36, 39, 41, 45, 47, 51, 54
7	1, 7, 9, 12, 17, 19, 22, 24, 25, 27, 28	1, 2, 6, 10, 19, 22, 26, 29, 30, 32, 36, 39, 41, 44, 46, 49, 54
6	3, 5, 9, 13, 15, 17, 19, 22, 25, 27, 28	1, 4, 7, 10, 20, 23, 27, 30, 32, 36, 39, 41, 45, 46, 49, 52, 54
5	3, 5, 9, 13, 14, 17, 19, 22, 24, 25, 28, 29	3, 5, 8, 14, 16, 17, 19, 22, 26, 29, 30, 32, 36, 39, 42, 43, 45, 48, 51, 54
4	3, 5, 8, 11, 13, 14, 17, 19, 21, 23, 26, 29	2, 6, 12, 19, 21, 23, 27, 30, 33, 35, 39, 40, 42, 43, 44, 45, 46, 47, 50, 52, 54

Results in Table I and II Table I confirm the reduction in the number of PMUs using placement based on increasing channels of PMUs.

The case studied also conducted on IEEE 118-bus system and 300-bus system, with limit of PMU channels are 10, the optimal placement of PMUs for IEEE 118-bus system are: 3, 5, 9, 12, 15, 17, 20, 23, 28, 30, 36, 40, 44, 46, 51, 54, 57, 62, 63, 68, 71, 75, 77, 80, 85, 86, 90, 94, 101, 105, 110, 114. For IEEE 300-bus system are 1, 2, 3, 11, 12, 15, 17, 22, 23, 25, 26, 27, 33, 37, 38, 43, 48, 49, 53, 54, 55, 58, 59, 60, 62, 64, 65, 68, 71, 73, 79, 83, 85, 86, 88, 92, 93, 98, 99, 101, 110, 112, 113, 116, 118, 119, 128, 132, 135, 138, 139, 143, 145, 148, 149, 152, 157, 163, 167, 173, 183, 187, 188, 189, 190, 193, 196, 202, 204, 208, 210, 211, 213, 216, 217, 219, 222, 226, 228, 263, 267, 269, 270, 272, 273, 274, 276, 280, 281, 282, 283, 284, 285, 286, 287, 294.

V. Construction of System Restoration Strategy with PMU Measurements

A. Contributions of PMU for System Restoration

Time stamped system information from PMU is significantly benefit system restoration with all restoration stages. Generally, system restoration is divided into three stages, i.e., preparation stage, system restoration stage and load restoration stage. PMUs have different contributions for different stages.

At preparation stage, evaluation of system status and definition of target system is the major objective. PMUs can help implement the objective of this stage by providing precise system information. With PMUs information, the remaining system is identified and available components of the system can be detected as well. By the state estimation technologies associated with PMUs, the status of the system can be precisely understood. Especially, the most essential issue for system restoration-the initial sources, can be detected. This information will help operator to initialize the restoration strategy. Furthermore, by detecting available components of the system, the target system can be designed.

At system restoration stage, reintegration of the bulk network is the major objective. Some loads will be restored as a means to maintain the stability of the system. Benefits from PMUs are: to monitor system status to establish decisions; to monitor system status after each action to ensure security of the system; to monitor standing angles of the branches to ensure stability of the system; to monitor bus voltage magnitudes and phase angles to evaluate system voltage stability and small signal stability; and to estimate transient stability before each action.

At load restoration stage, as the last stage of system restoration, PMUs can also benefit it by providing information to support each restoration action. The benefits are: to monitor steady-state variables of system, i.e., voltage, current, and power flow calculated by voltage and current, to ensure security of the system; to monitor frequency during pickup each load; to evaluate voltage stability during each load pickup by the variables provided by PMUs; to assess small signal stability of system after a big load pickup; and evaluate transient stability for load pickup.

To fully implementation these benefits of PMUs for system restoration, PMUs information should achieve following requirements:

- To optimize placement of PMUs to achieve complete of observability of the gird;
- To establish coordination of PMUs information during system restoration;
- To design reasonable operation methods to ensure workability of PMUs following a outage;

Algorithm 1 presented in this paper can be used to fully implement the first requirement. For the last two requirements, more sophisticated algorithms are required.

B. Restoration Oriented PMU Placement

To acquire sufficient and accurate information during system restoration, direct measurements from critical components are required. From system restoration's viewpoint, the most important components are generating units and critical loads. The PMU placement problem in this context is minimize numbers of PMUs subject to the complete observability and all important components are equipped PMUs. Based on this idea, the Algorithm 1 is modified as follows:

Algorithm 2:

$$\min \quad \mathbf{f}^T \mathbf{X} \tag{4}$$

$$\text{s.t.} \quad \mathbf{CX} > 0 \tag{5}$$

where **C** and **X** are the same as Algorithm 1; **f** is defined as: if a generating unit or critical load is connected at bus i, $f_i = -M$ (M is a large positive number); else based on the rules defined in Algorithm 1.

By setting different factors in vector , correlative elements of generating units and loads will be sent as a negative number. As a minimize problem, the installation on these buses can be ensured.

Table III: Restoration Oriented Optimal Placements of PMU in IEEE 118-Bus and 300-Bus Systems

System	Bus with Generating Units	PMU Placement
IEEE 118-BUS	1, 4, 6, 8, 10, 12, 15, 18, 19, 24, 25, 26, 27, 31, 32, 34, 36, 40, 42, 46, 49, 54, 55, 56, 59, 61, 62, 65, 66, 69, 70, 72, 73, 74, 76, 77, 80, 85, 87, 89, 90, 91, 92, 99, 100, 103, 104, 105, 107, 110, 111, 112, 113, 116	1, 4, 6, 8, 10, 12, 15, 18, 19, 22, 24, 25, 26, 27, 31, 32, 34, 36, 40, 42, 45, 46, 49, 53, 54, 55, 56, 59, 61, 62, 65, 66, 69, 70, 72, 73, 74, 76, 77, 80, 85, 87, 89, 90, 91, 92, 96, 99, 100, 103, 104, 105, 107, 110, 111, 112, 113, 116
IEEE 300-BUS	8, 10, 19, 55, 63, 69, 76, 77, 80, 88, 98, 103, 104, 117, 120, 122, 125, 126, 128, 131, 132, 135, 149, 150, 155, 156, 164, 165, 166, 169, 170, 177, 192, 199, 200, 201, 206, 209, 212, 215, 217, 218, 220, 221, 222, 247, 248, 249, 250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260, 261, 262, 263, 264, 265, 267, 292, 294, 295, 296	7, 8, 10, 11, 16, 19, 23, 25, 27, 35, 37, 48, 51, 54, 55, 58, 60, 62, 63, 64, 68, 69, 71, 72, 73, 76, 77, 80, 81, 85, 88, 92, 93, 98, 99, 101, 103, 104, 109, 113, 117, 118, 120, 122, 125, 126, 128, 131, 132, 135, 138, 143, 145, 148, 149, 150, 155, 156, 157, 164, 165, 166, 169, 170, 173, 177, 183, 187, 189, 190, 192, 194, 199, 200, 201, 205, 206, 209, 212, 213, 215, 217, 218, 219, 220, 221, 222, 226, 228, 247, 248, 249, 250, 251, 252, 253, 254, 255, 256, 257, 258, 259, 260, 261, 262, 263, 264, 265, 267, 268, 269, 270, 272, 273, 274, 276, 292, 294, 295, 296

For the IEEE 14-bus system illustrated in Fig.3, only considering generating units at bus 1, 2, 3, 6, and 8, the solution is: 1, 2, 3, 6, 8, and 9. All the generating units are installed. The complete observability is obtained as well. Compared with the result in Section IV, more PMUs are installed because all generating units are equipped with PMUs.

This algorithm is also tested on IEEE 30-bus and 57-bus systems. In IEEE 30-bus system, generating units are installed at bus 1, 2, 13, 23, and 27. One of the solutions for PMU installation is: 1, 2, 6, 9, 10, 12, 13, 18, 22, 23, 25, and 27. For IEEE 57-bus system, generating units are installed at bus 1, 2, 3, 6, 8, 9, and 12. One of the solutions for PMU installation is: 1, 2, 3, 6, 8, 9, 12, 15, 19, 22, 26, 29, 30, 32, 36, 39, 41, 45, 47, 50, and 53. For these two systems, similar results as in IEEE 14-bus system are obtained. With one more constrain, more PMUs are needed for complete observability. For IEEE 118-bus system and 300-bus system, the results are listed in Table III.

C. Establish Restoration Strategy with PMU Measurements

As described in part B, for the purpose of system restoration, with complete observability by PMU, all of the buses with generating units and critical loads are equipped PMUs. During the restoration process, establishment of each transmission path should ensure observability. Currently, the restoration decision support systems for transmission path establishment only consider steady-state or dynamic constrains, and information acquisition methods are not involved yet [11, 12]. In this context, usually, the charging current of each path is employed as the weight. As a result, the shortest path means the lowest risk for voltage violation, as proposed in [11, 12]. In this paper, a sophisticated algorithm, which integrates PMU information and charging current of each line, is proposed. This method is modified from Algorithm 2 of [11]. To obtain an objective bus B from the energized block set Ω_E to, following steps are used.

Step 1: Establish the distance matrix, i.e.,

$$\mathbf{DM} = \left[d_{ij} \right] = \begin{cases} 0, & \text{if } i \text{ and } j \in \mathbf{\Omega_E} \\ \text{charging current of line } i-j, & \text{if } i \text{ or } j \notin \mathbf{\Omega_E} \cap i \text{ and } j \\ & \text{are observed with PMU} \\ \text{a large number } \rho, & \text{if } i-j \text{ is a transformer} \\ & \cap\ i \text{ or } j \notin \mathbf{\Omega_E} \cup i \text{ or } j \\ & \text{are ont observed with PMU} \end{cases} \tag{4}$$

Step 2: $\forall i \in \Omega_E$, find the shortest path from i to B by Dijkstra's algorithm [13] as $\{n_k,\ k = 1, 2, \cdots, m, \text{ and } n_1 = i\}$, where is a bus through the shortest path and the number of buses is m;

Step 3: Find $n_\lambda \in \Omega_E$ and $n_{\lambda+1} \notin \Omega_E$, where $1 \le \lambda < m$;

In this step, $n_{\lambda+1}$ is the first bus outside the block and all buses within the path after $n_{\lambda+1}$ are outside the block.

Step 4: Output $Path = \{n_k\}, k = \lambda+1, \lambda+2, \cdots, m$

The idea of this algorithm is to connect all buses within the block by zero length line first. Therefore, the shortest path from any bus within this block to the object bus is the shortest path from this block to that bus. For the path with unobservable bus, a large number is set as the penalty.

The proposed method is tested on IEEE 14-bus system. As analyzed in part B of this section, PMUs are installed at bus 1, 2, 3, 6, 8, and 9. Assume only the generating unit at bus 1 is a black start unit, according the algorithm proposed in [11], the sequence of restoration is shown in Table IV. At each step, observability is obtained.

Table IV: Sequence for Restoration of Generating Units

Step	Restoration Action	Path
1	Restart BS at 1	-----
2	Crank NBS at 2	1—2
3	Crank NBS at 6	1--5--6
4	Crank NBS at 8	2--4--9--7--8
5	Crank NBS at 3	4 --3

VI. CONCLUSIONS

Electric power grids are increasingly dependent on information and communications technology for the operation and control of physical facilities. Power system restoration is well recognized as one of the major technologies to improve reliability of power systems. All restoration strategies should be established and implemented with accurate system information acquisition. As the state-of-the-art information monitoring infrastructure, PMU provides a reliable and accurate during system restoration. In this paper, for the purpose of system restoration, after review the development of PMU, three algorithms are proposed based on PMU measurements. By solving binary optimization models, the PMU placement schemes to achieve complete observability of the system for regular operating conditions and restoration process are obtained. An algorithm for finding restoration sequence with PMU measurements is also proposed in this paper. Case studies on different test systems validate the proposed algorithms.

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